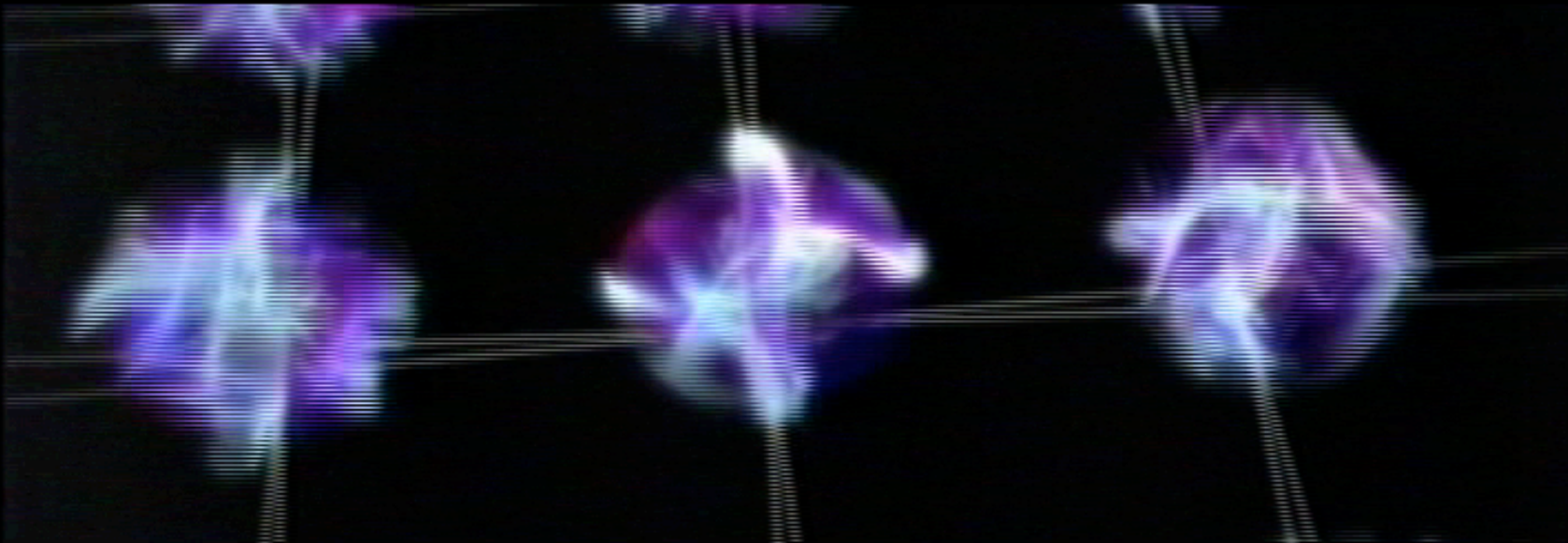


the search for extra dimensions



Joe Lykken
Fermilab/University of Chicago



extra dimensions?

is this science?

hyperspace is no joke



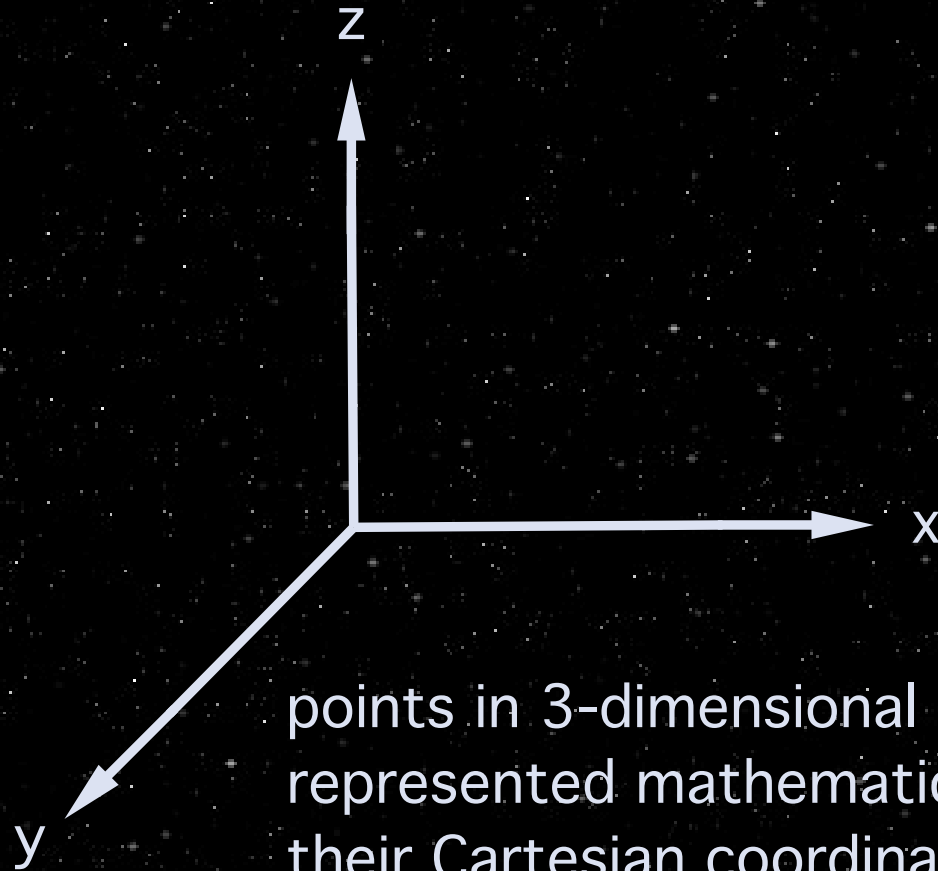
outline

- what is a dimension?
- the fathers of extra dimensions
- string theory
- Kaluza-Klein modes
- braneworlds
- extra dimensions at Fermilab

what is a dimension?



Rene Descartes



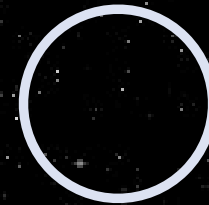
points in 3-dimensional space
represented mathematically by
their Cartesian coordinates x,y,z

the power of analytic geometry



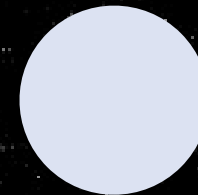
equations replace pictures:

$$x^2 + y^2 = 1$$



circle

$$x^2 + y^2 + z^2 = 1$$



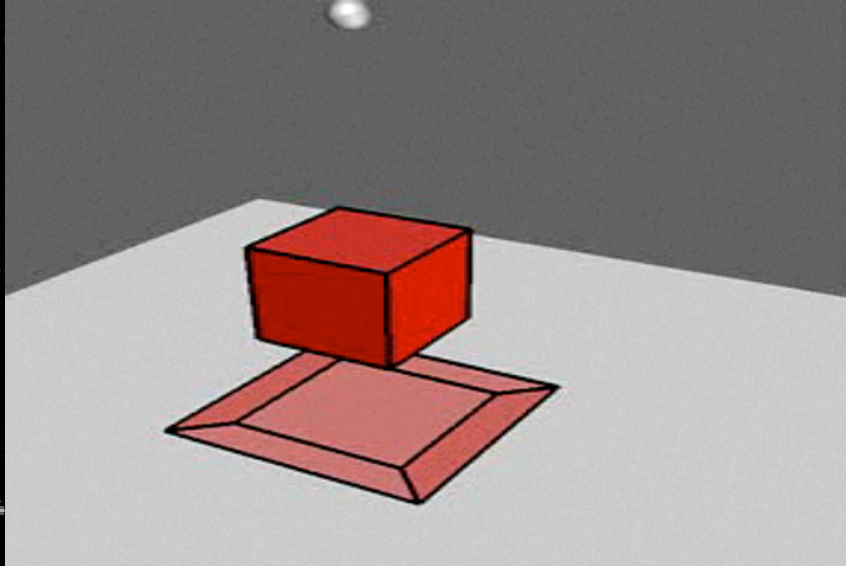
sphere

$$x^2 + y^2 + z^2 + w^2 = 1$$

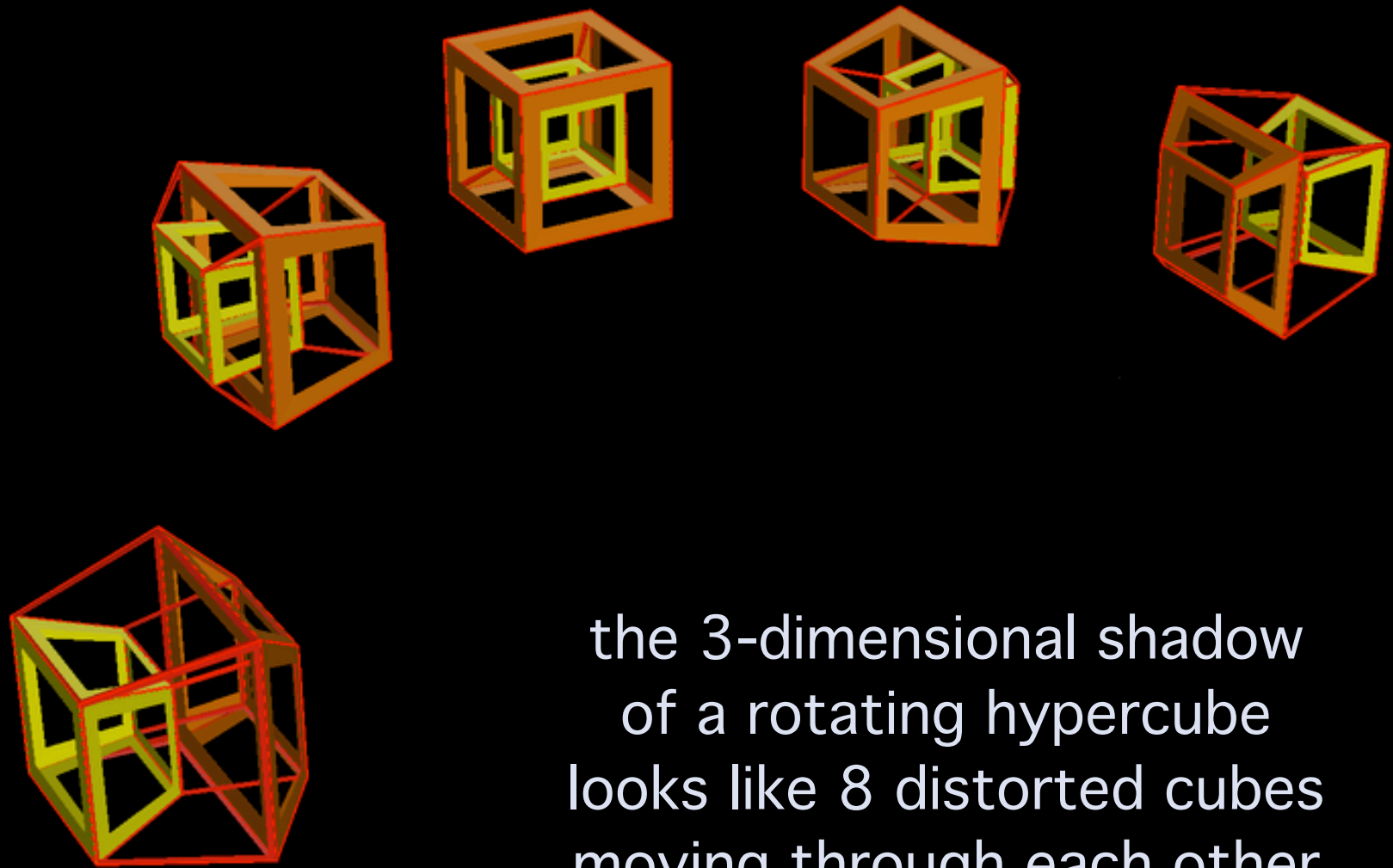
hypersphere

we can also make pictures of the
3-dimensional shadows of 4-dimensional objects

this is like the more familiar case of
2-dimensional shadows of 3-dimensional objects



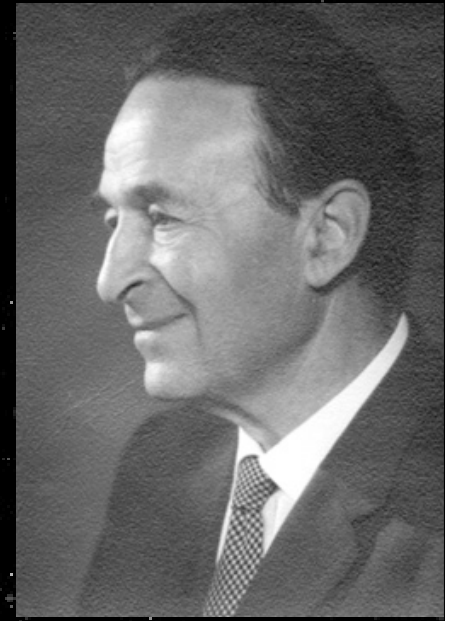
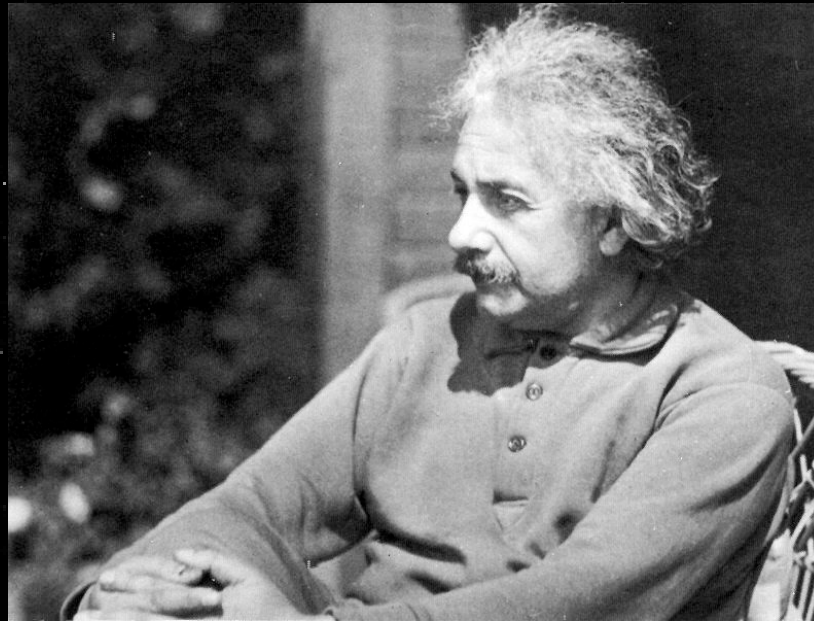
the shadow of a
rotating cube looks like
6 distorted squares
moving through each other

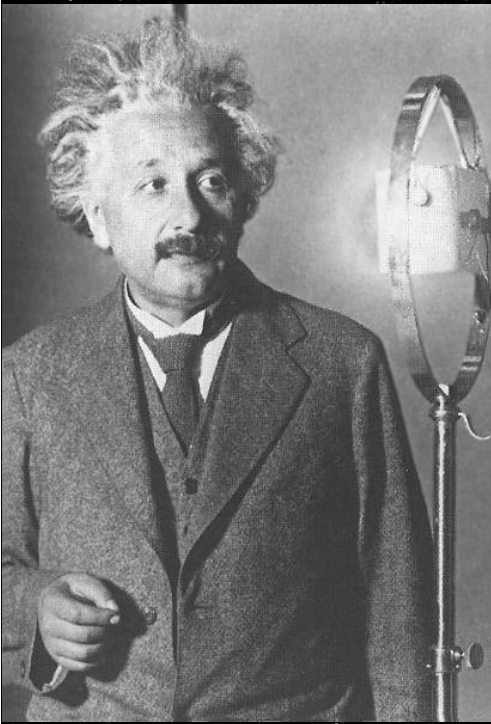


the 3-dimensional shadow
of a rotating hypercube
looks like 8 distorted cubes
moving through each other

- extra dimensions make sense in mathematics
- do they also make sense in physics?
- could there be more physical dimensions than the three that we see?
- if so, why are the extra dimensions hidden?
- and what are they good for?

the fathers of extra dimensions

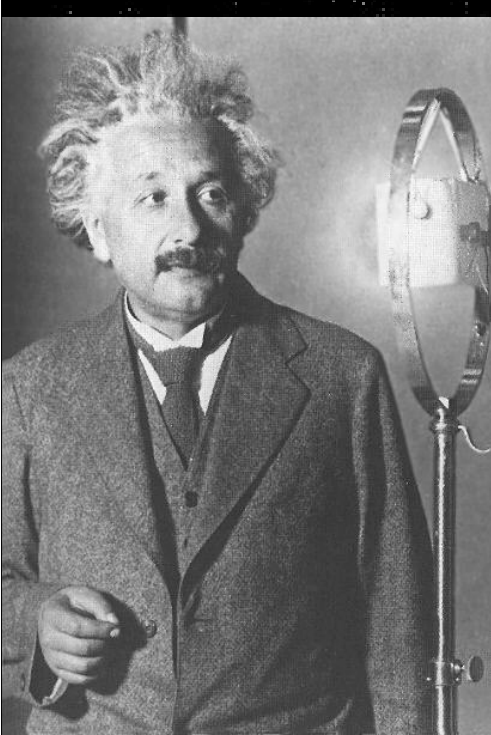




“time is the fourth dimension”

A. Einstein, 1905

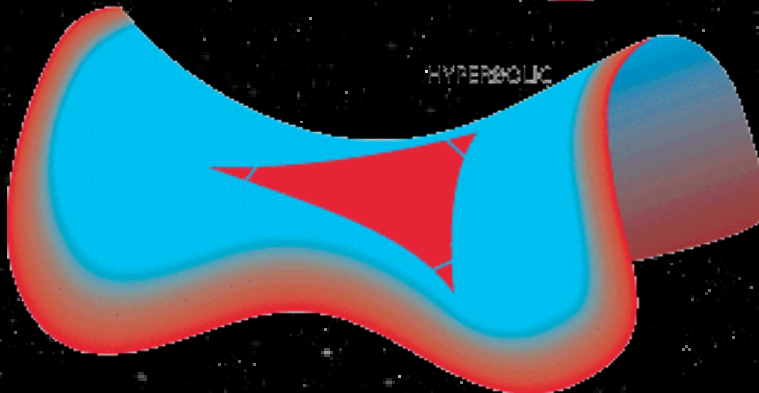
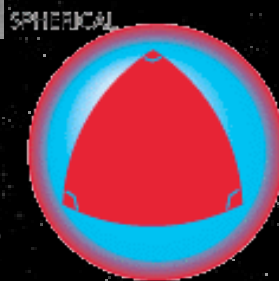
- four dimensional space-time: x,y,z, and t
- there is a universal constant, called “c”, which converts measurements of time into measurements of space.
- $c = 299,792$ kilometers per second



“space has a shape”

A. Einstein, 1911

- the curvature of space is revealed by measuring the total angle inside a triangle
- the shape of space is determined by matter and energy
- gravity is nothing more than curvature of space-time

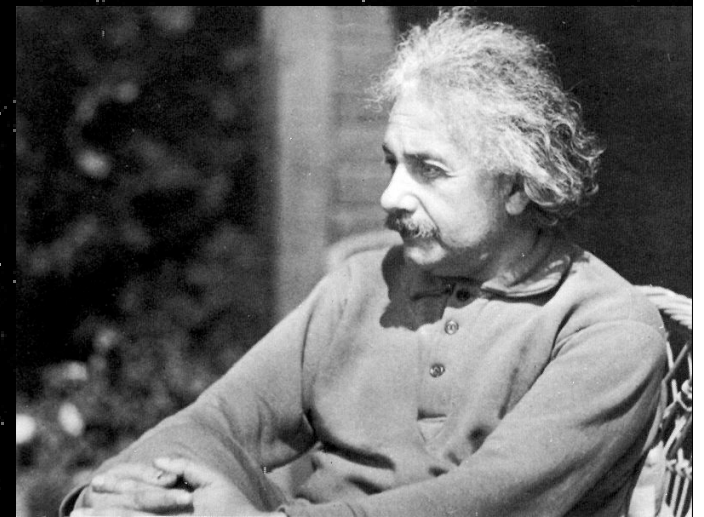




the fifth dimension

in 1914, Finnish physicist Gunnar Nordstrom showed that gravity and electromagnetism could be unified as a single force, in a theory with an extra spatial dimension

Einstein ignored Nordstrom's idea, probably because it used Nordstrom's own theory of gravity, which was then in competition with Einstein's

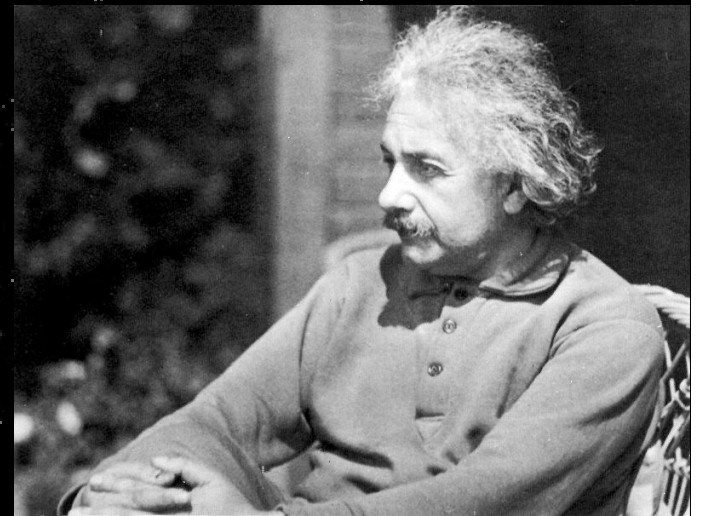




the fifth dimension

in 1919, Polish mathematician Theodor Kaluza again introduced the idea of a fifth dimension, but this time using Einstein's theory of gravity - this made all the difference:

“The idea of achieving [a unified theory] by means of a five-dimensional cylinder world never dawned on me... At first glance I like your idea enormously”



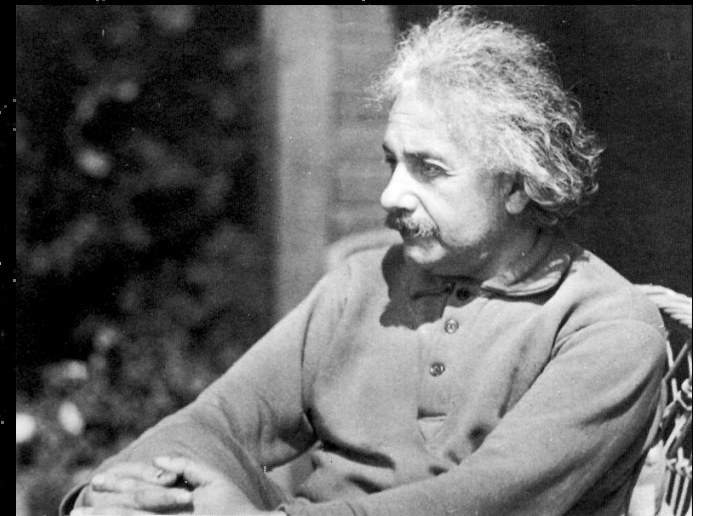


the fifth dimension is a circle

Nordstrom, Kaluza, and Einstein all assumed that the fifth dimension wasn't real, since otherwise why don't we see it?

in 1926, Swedish physicist Oskar Klein proposed that the fifth dimension was real, but too tiny to see

“Klein's paper is beautiful and impressive.”





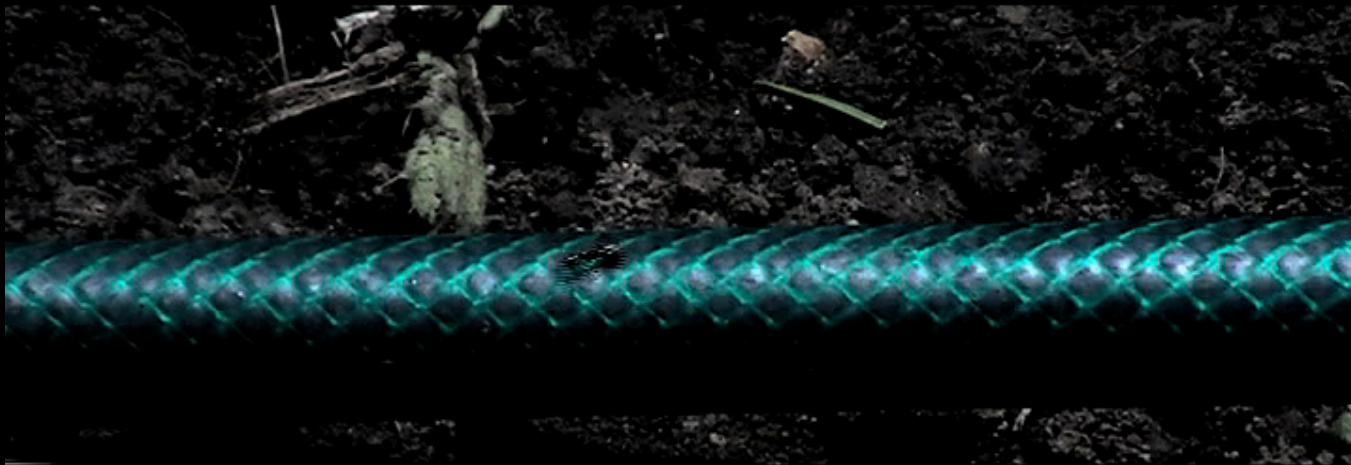
A simple example:

the tightrope walker sees
the tightrope as having only
one spatial dimension

the tightrope walker can
only move in one direction,
(back and forth)

the extra dimension is a circle?

but an ant on a tightrope
can move both back and forth
AND around a circle



the ant sees an extra dimension
= an extra tiny circle at every point
along the tightrope



the fifth dimension is a circle

Klein computed how small the circle of the 5th dimension should be, in order to give a unified theory of gravity and electromagnetism

the answer is:

[illegible]

nobody thought about
extra dimensions for 50 years





John Schwarz

string theory

in the 1970s some
visionary physicists began
to construct a
radical new theory



Pierre Ramond

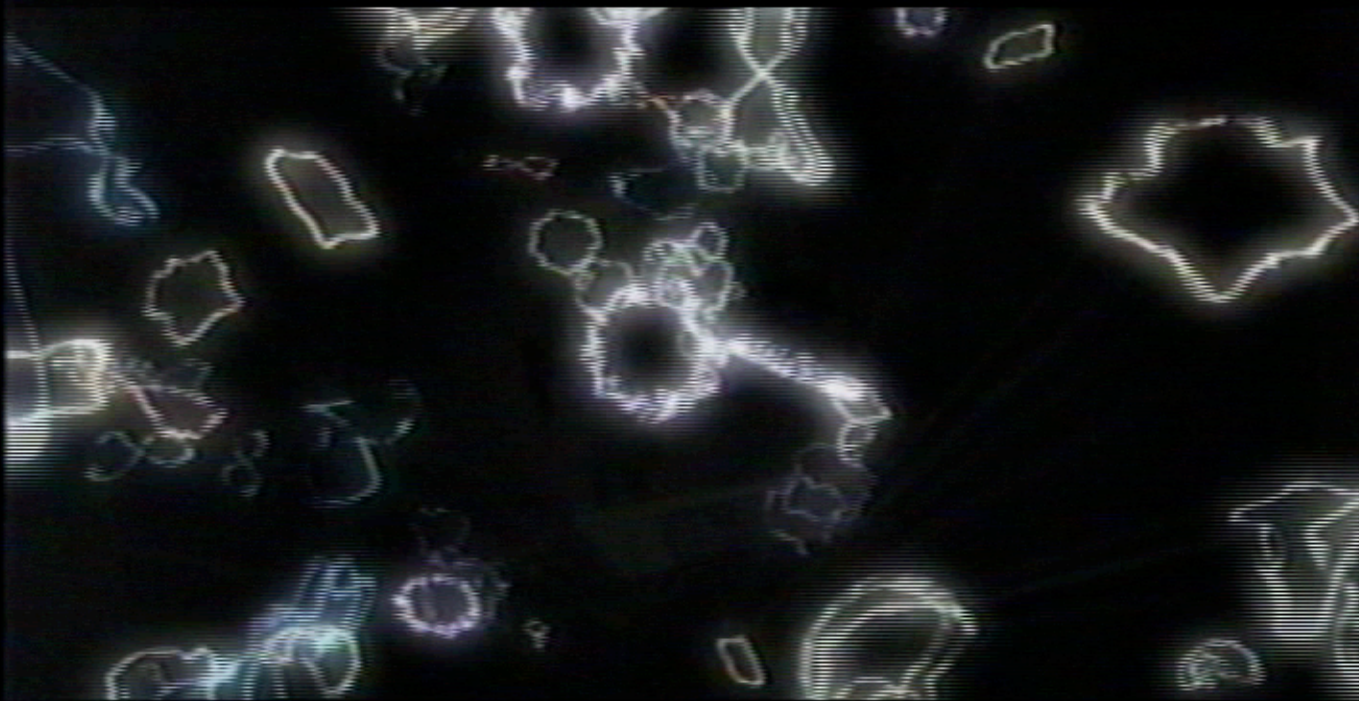
in this theory all of the
elementary particles are
just different vibrations of
microscopic strings



Gabriele Veneziano

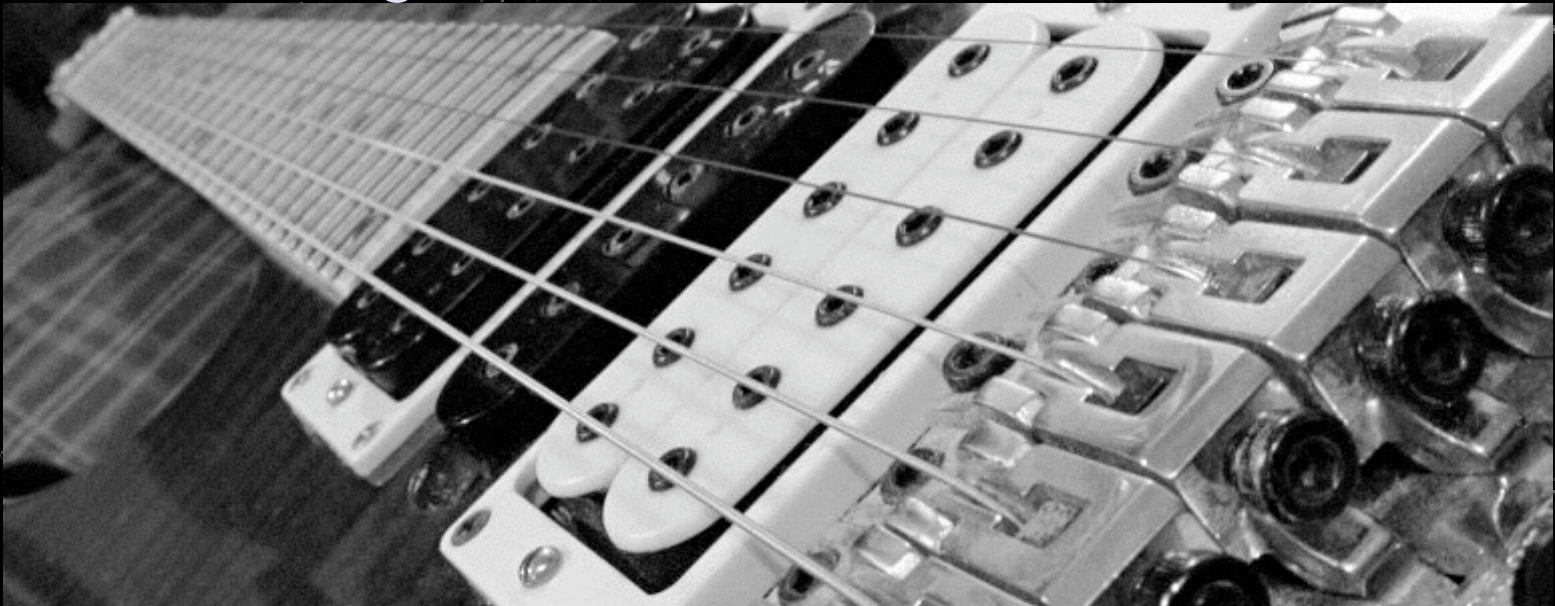
in string theory

electrons, quarks, photons, gravitons, neutrinos, etc are
all different vibrations of one kind of microscopic string:
the superstring



what are superstrings?

- like guitar strings, they are elastic, and they have tension
- like the pitch and overtones of a guitar string, superstrings have their own special vibrations, called string modes



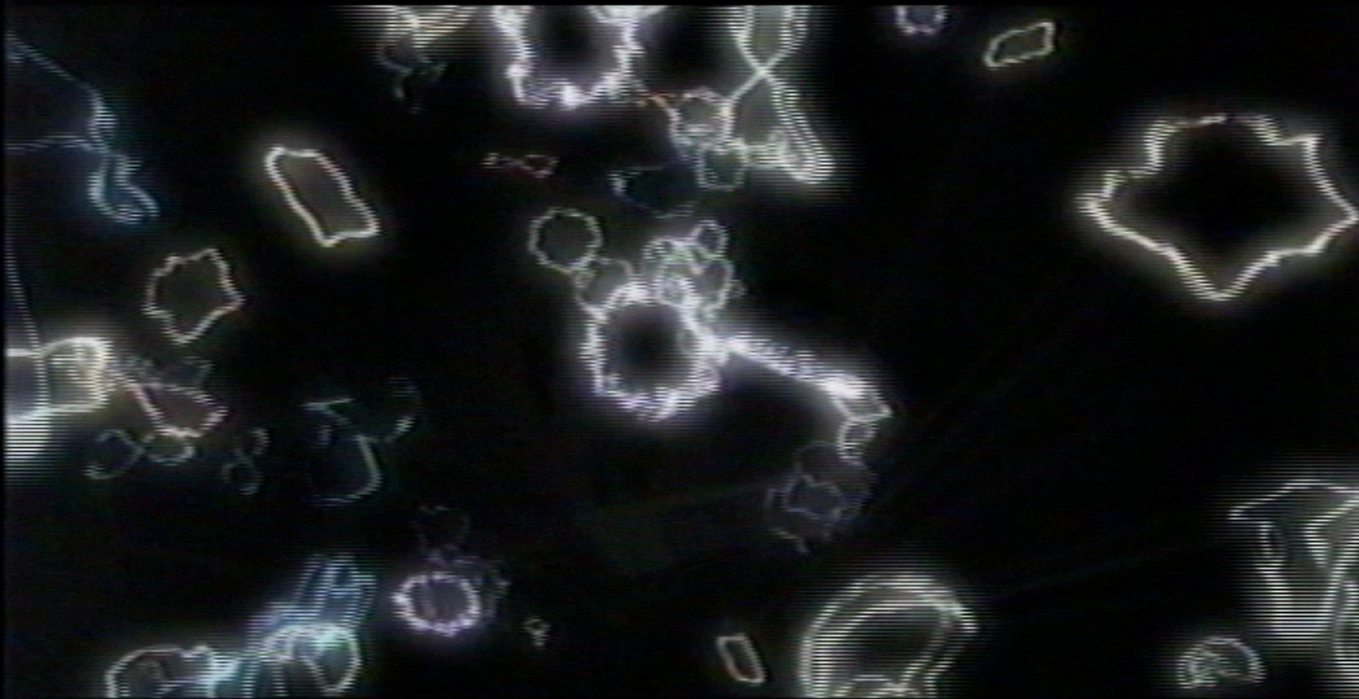
what are superstrings?

- unlike guitar strings, superstrings are not made out of anything, and they have zero thickness!
- unlike guitar strings, which are stretched by tuning pegs, superstrings have to stretch themselves!



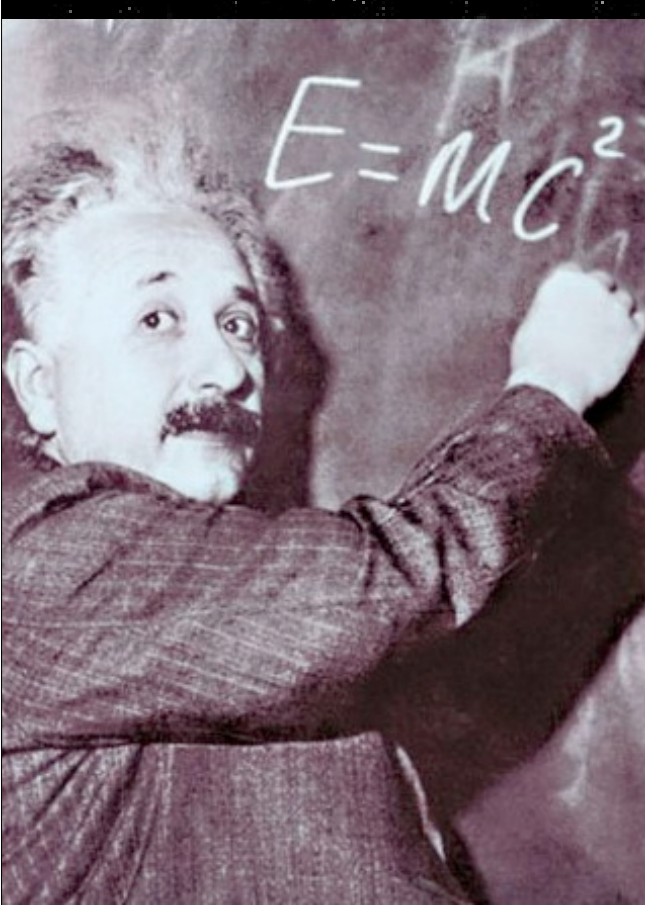
quantum superstrings

superstrings stretch themselves by wiggling.
quantum mechanics says that a microscopic string
will always be wiggling, at least a little bit



particles from strings

- to us, a microscopic wiggling string looks like a particle, because the string is too small for us to notice either its size or its wiggles
- the momentum of the string vibrations, and the energy of the string stretching, will look to us like the mass of the “particle”
- this mass can be computed from Einstein’s famous formula:



actually we need the more complete version of this formula:

this formula tells us the mass of a “particle” in terms of the energy and momentum of the vibrating superstring

$$E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 = (mc^2)^2$$



John Schwarz

one small problem:

some elementary particles (the photon, the graviton) are massless

for superstrings, this requires a delicate cancellation between the energy and momentum of stretching and vibration

in the original version of string theory, the cancellation didn't work!

$$E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 \neq 0?$$



John Schwarz

only two ways to modify the quantum vibrations of a string:

- invoke supersymmetry, which reduces the quantum wiggles
- increase the number of spatial dimensions that the strings can wiggle in

only with 9 spatial dimensions can superstrings produce the particles that we see!

$$E^2 - (\mathbf{p}_x c)^2 - (\mathbf{p}_y c)^2 - (\mathbf{p}_z c)^2 = 0$$



John Schwarz

denied tenure at Caltech

superstrings: a great idea?



Pierre Ramond

fired from Fermilab

after 10 years of neglect,
string theory finally
became a hot idea in 1984

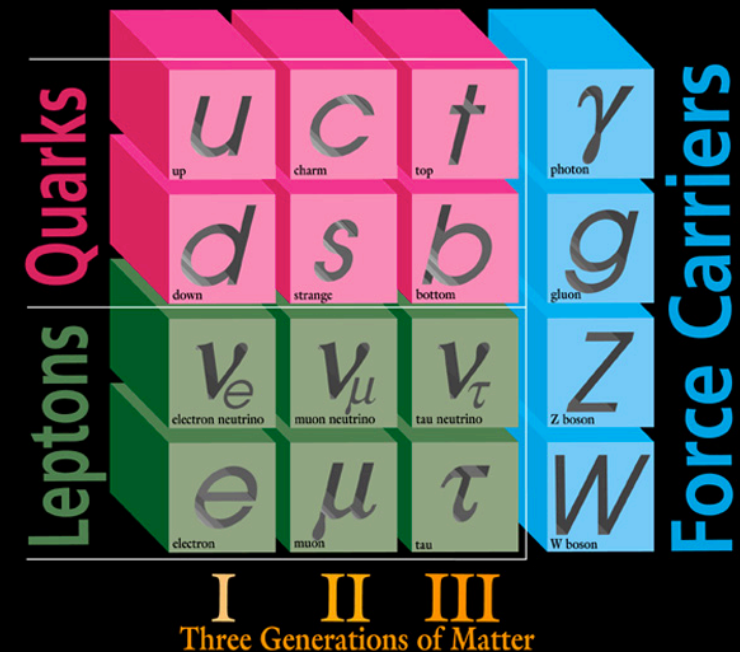
- string theory is very elegant mathematically
- but if we take string theory seriously, it makes a firm prediction that there are (many) extra dimensions of space
- is this reasonable?



too many particles

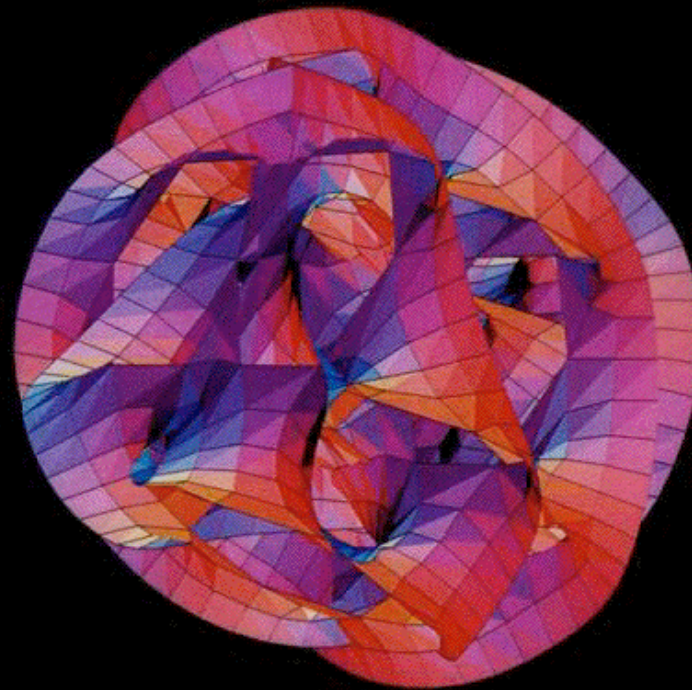
- so far, particle physicists have discovered 57 different elementary particles
- and these 57 particles are related to each other in complicated ways

something is wrong or missing in this picture...



the shape of extra dimensions
may explain the complexities
of particle physics

slice of a
6 dimensional Calabi-Yau
manifold

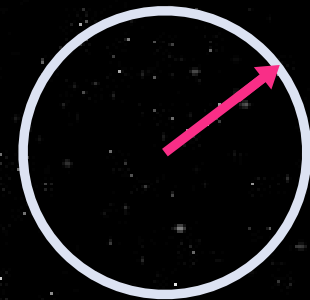


how do you detect an extra dimension?

- even if extra dimensions make sense in theory, it still isn't physics until you find a way to detect them in experiments
- this depends upon what is the physical mechanism that is hiding them
- let's explore Klein's idea that extra dimensions are hidden because they are tiny

Kaluza-Klein modes

- suppose an electron can move around a tiny 5th dimension
- it will have momentum from this motion
- quantum mechanics says that this momentum is quantized: it has to be a multiple of $1/R$
- this is like the quantized momentum of an electron in an atom

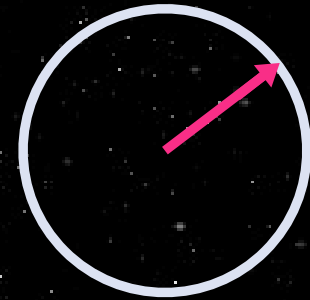


circle with radius R

$$p_5 = \frac{n}{R}$$

Kaluza-Klein modes

- if the extra dimension is tiny, we will not see the electron's motion around it
- as with the string wiggles, we will interpret the momentum from this motion as a contribution to the particle's mass:



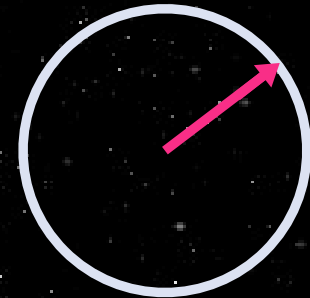
circle with radius R

$$p_5 = \frac{n}{R}$$

$$E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 = (p_5 c)^2 = \left(\frac{n \hbar c}{R}\right)^2$$

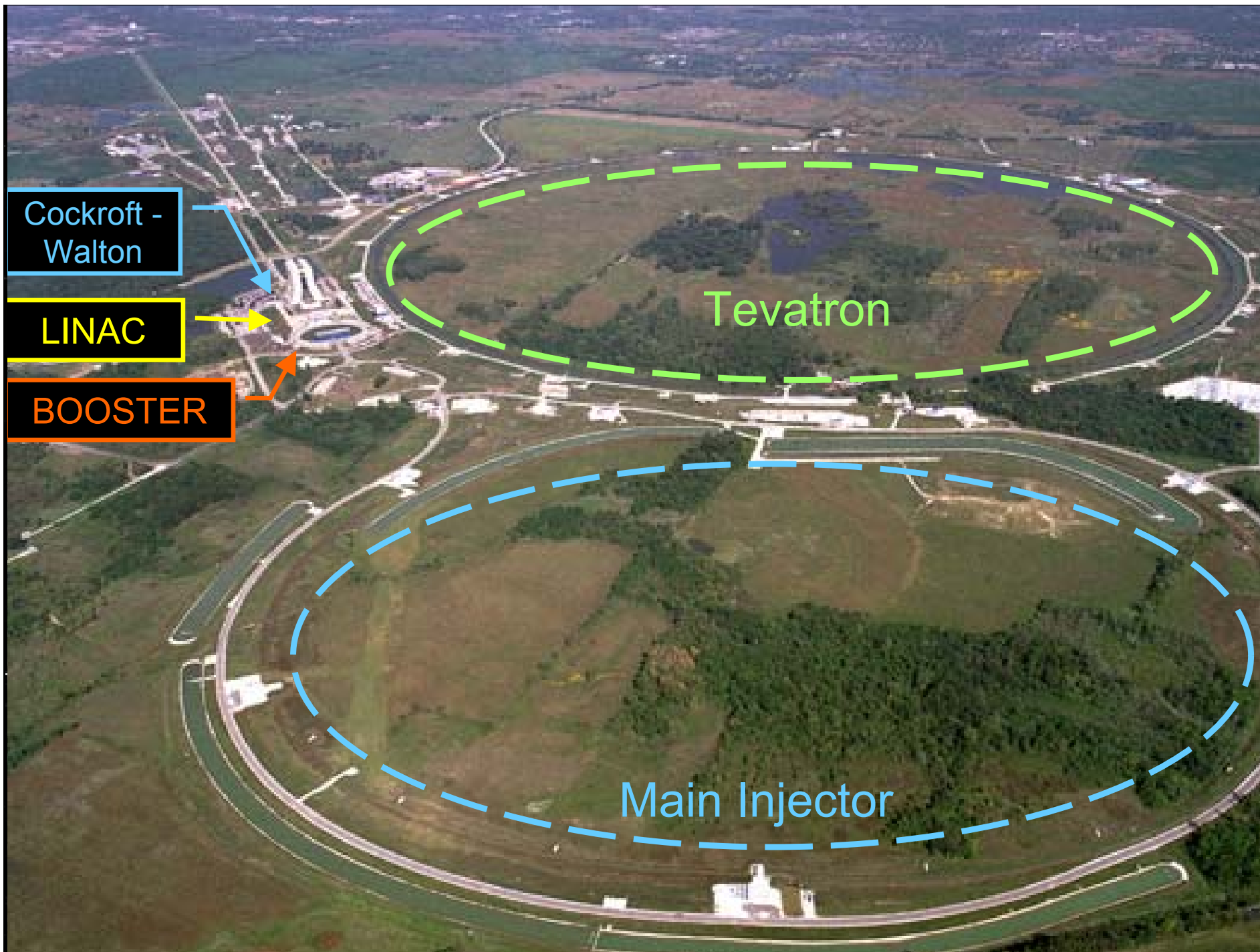
Kaluza-Klein modes

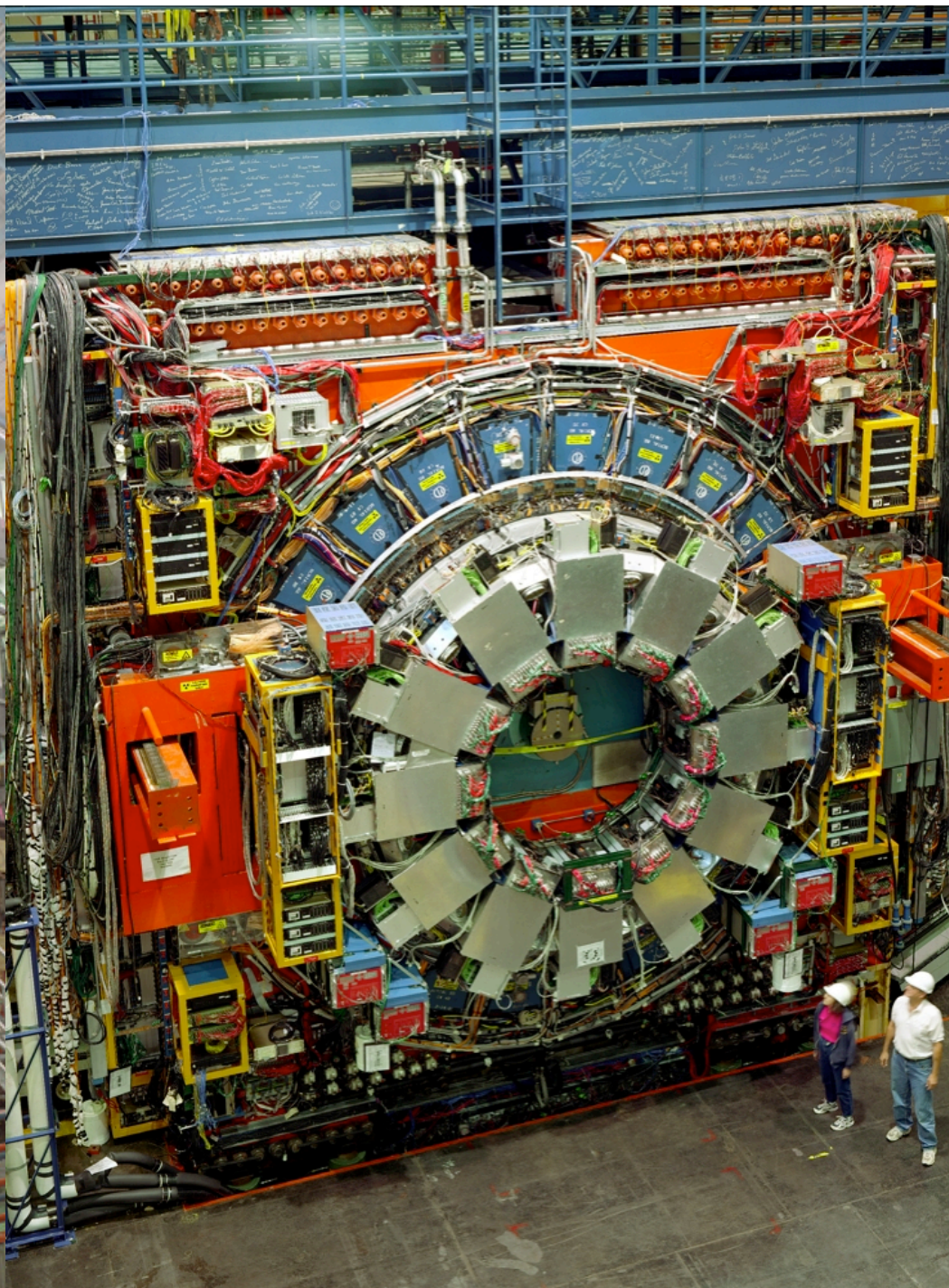
- what we will detect is a much heavier version of an electron
- we call this new heavy particle a Kaluza-Klein mode
- the smaller the extra dimension is, the heavier these new particles will be



circle with radius R

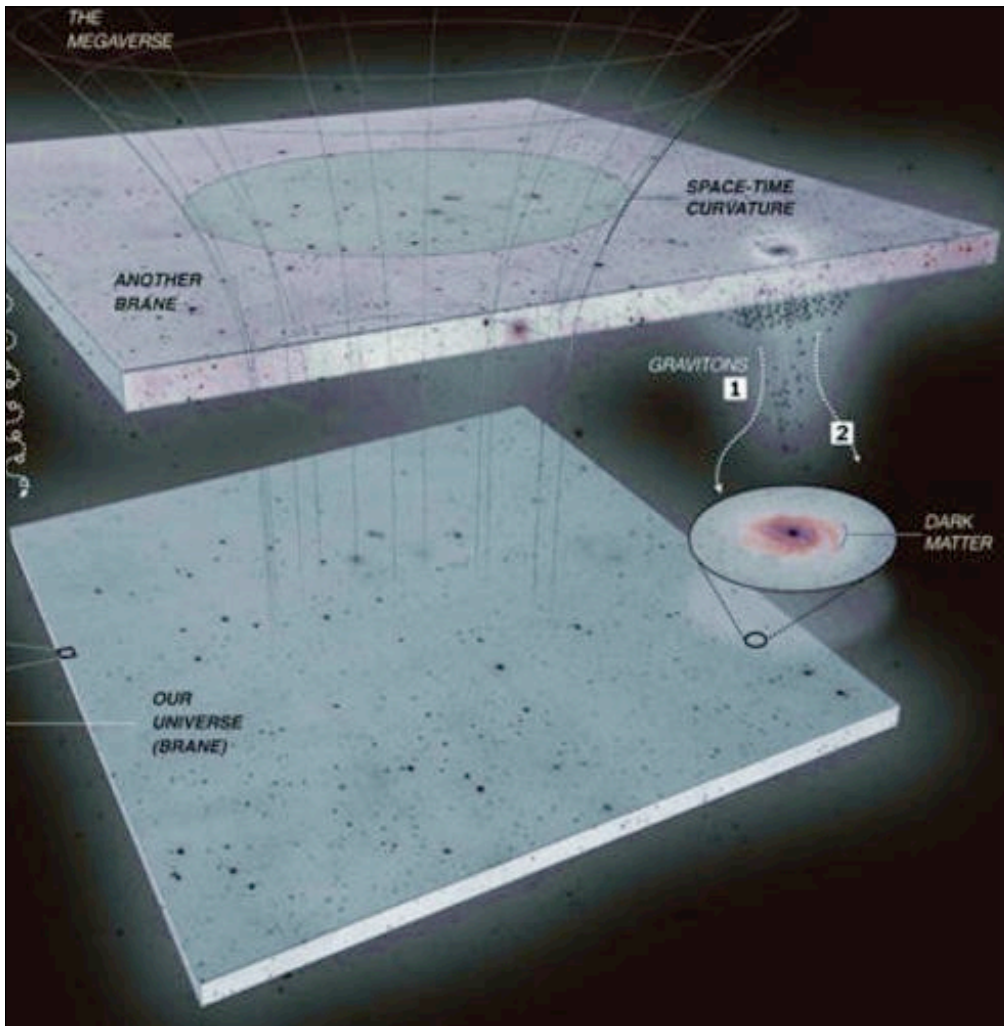
$$p_5 = \frac{n}{R}$$





one small problem:

- we don't know which elementary particles can move in the extra dimensions
- so we don't know what kind of Kaluza-Klein modes to look for
- string theory suggests that perhaps none of the particles that we are made of can move in extra dimensions!

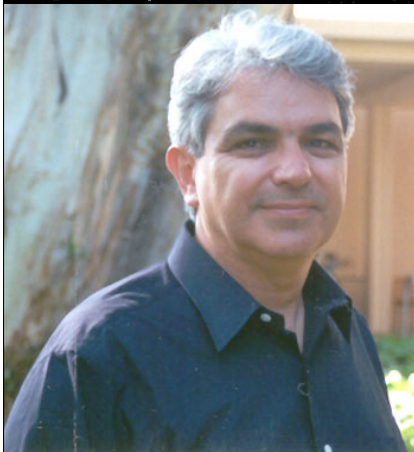


the braneworld

only gravitons and exotics
move in the “bulk” of the
extra dimensional universe

ordinary particles are trapped on a brane and can't move in the
extra dimensions

- if the braneworld idea is correct, the extra dimensions may be large!
- only experiments with gravity or gravitons will detect the presence of extra dimensions



Savas Dimopoulos



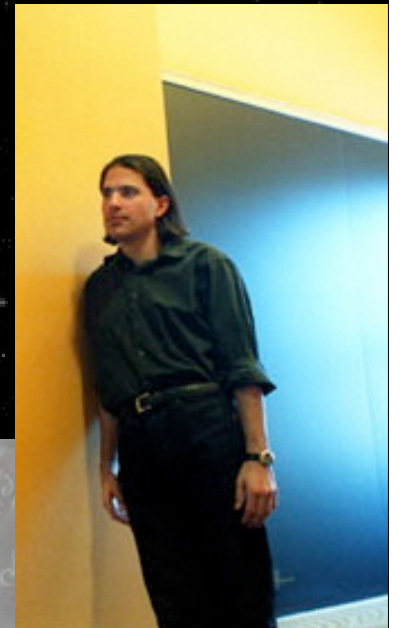
Gia Dvali



Lisa Randall



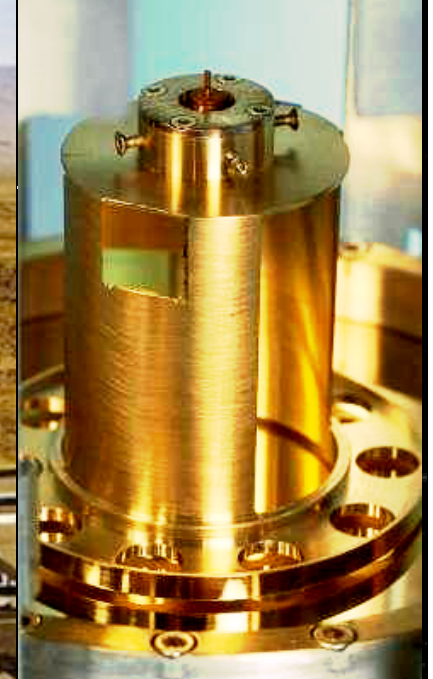
Raman Sundrum



Nima
Arkani-Hamed

Kaluza-Klein gravitons

- if (some of) the extra dimensions are large, the Kaluza-Klein modes of the graviton may be lighter particles, not heavy particles
- in that case you may be able to detect them without using particle accelerators

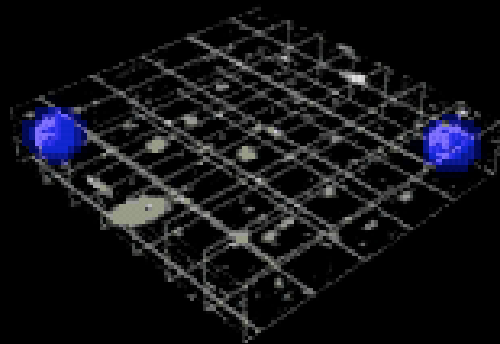


extra dimensions at Fermilab

- particle accelerators are our most powerful tools for exploring extra dimensions
- if Klein's idea of tiny extra dimensions is correct, we can still detect them as long as their size is no smaller than .00000000000000000001 centimeters!
- if the braneworld is correct, we can produce Kaluza-Klein gravitons at particle colliders like the Tevatron

one small problem:

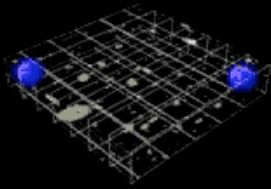
- in the braneworld scenario, the Kaluza-Klein gravitons that we produce will disappear into the extra dimension:



shoes in extra dimensions



shoes in extra dimensions



an experimental challenge



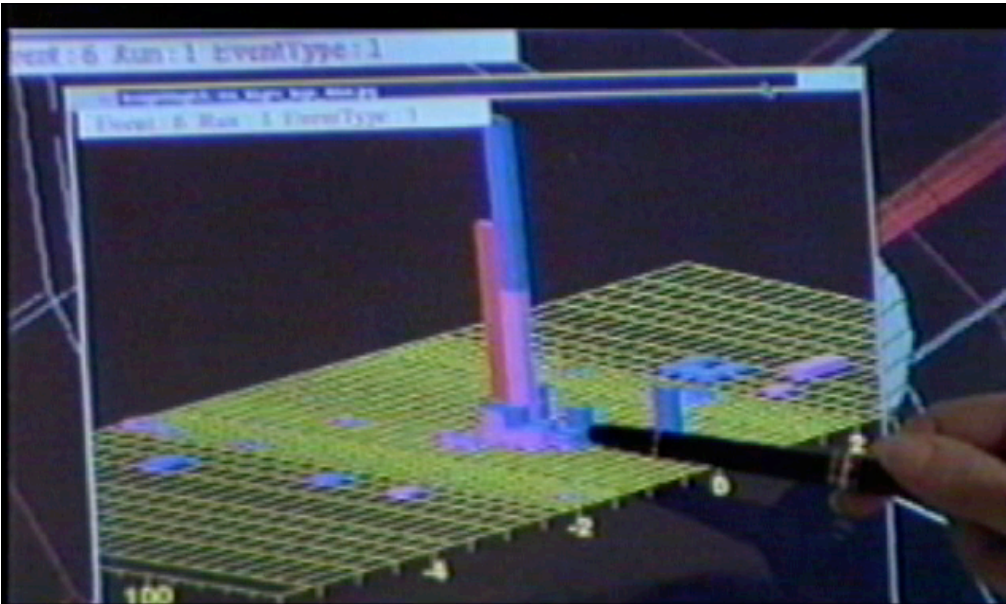
Maria Spiropulu



Greg Landsberg

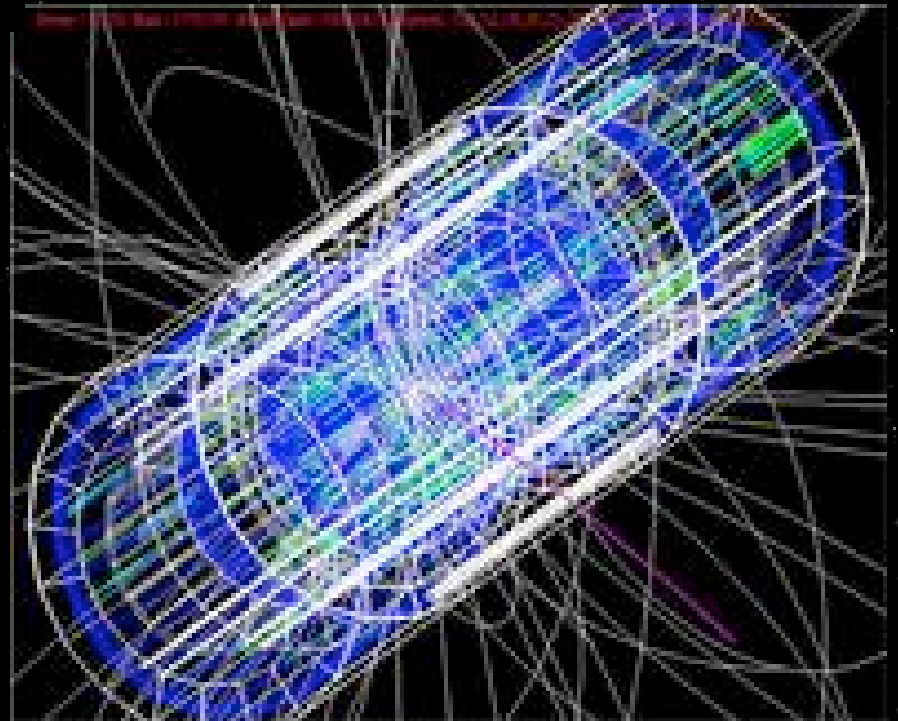
down in the tunnel



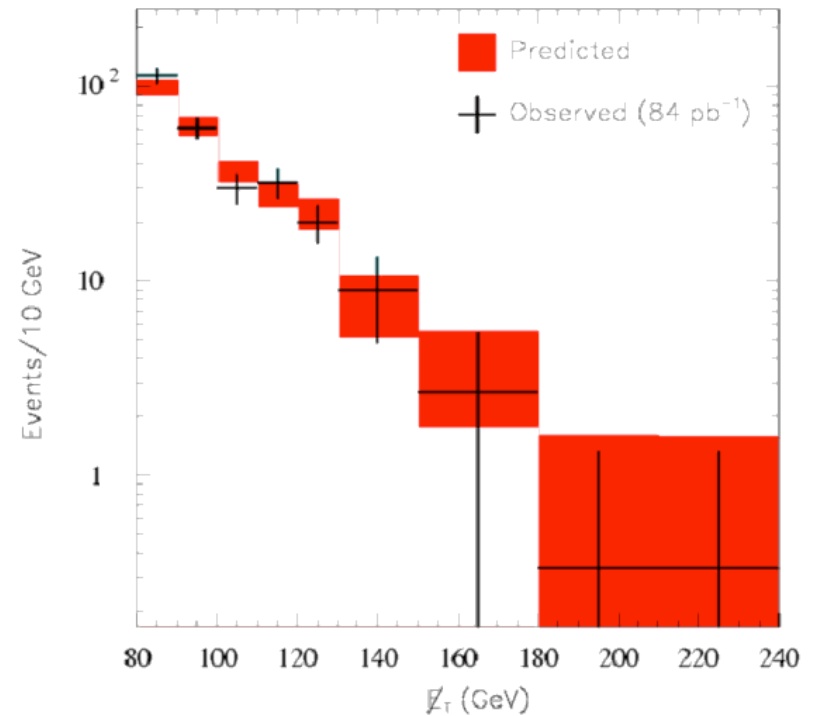
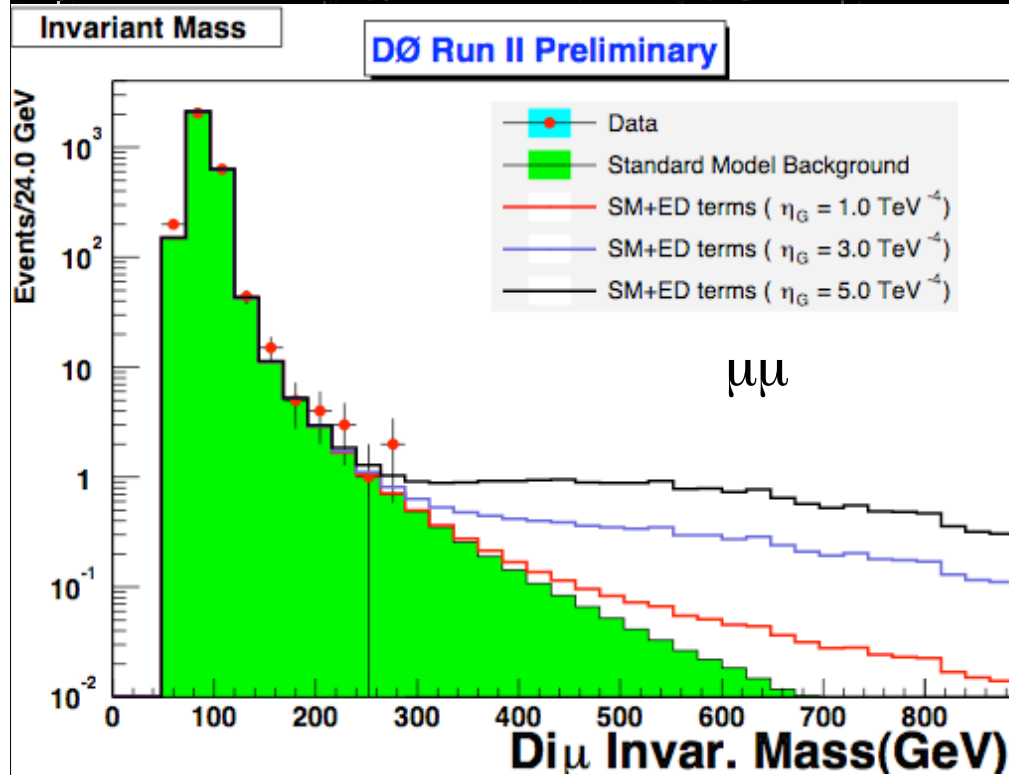


you have to sift
through trillions
of “events”

to find the rare
events that have
new particles or
new physics



what does the Tevatron data show so far?



the search continues...

Tevatron is running now -
LHC collider at CERN turns on in 2007
with 7 times the energy

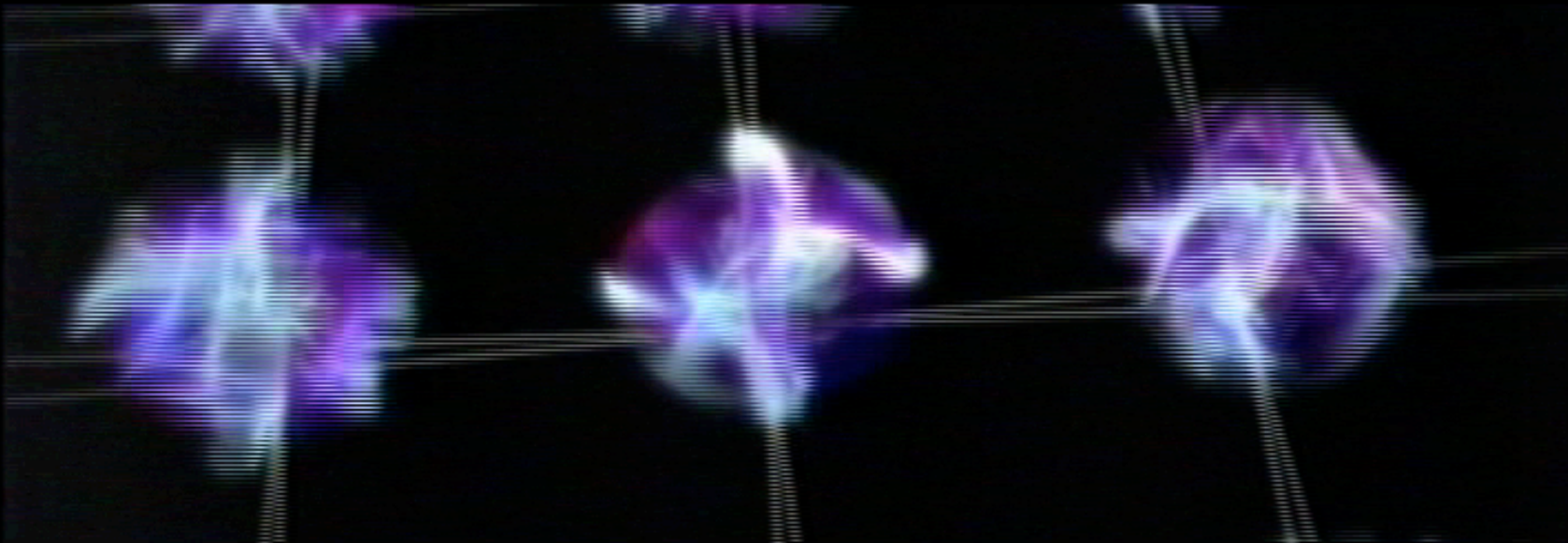


the universe: traditional view



← you are here

the search for extra dimensions



Joe Lykken
Fermilab/University of Chicago